This version compiled 28th August 2023

AN ANALYSIS OF THE KH-47M2 KINZHAL'S FLIGHT PERFORMANCE AND A PATRIOT PAC-2 MISSILE'S CHANCES OF A SUCCESSFUL INTERCEPT

Anders F. Jonsson
M.Sc. Aeronautical Engineering (Ret.)
Royal Institute of Technology, Stockholm

Abstract

This paper analyses a scenario in which a Kh-47M2 Kinzhal is fired from an aircraft[1] from an altitude of 12 km and at a speed of M=1 and based on the resulting flight profile if it's probable that Kinzhal missiles have been successfully intercepted by Ukrainian MIM-104 Patriot systems as reported in the media. In summary, the conclusions are that it would be a stretch to call the Kinzhal a hypersonic missile, and that these missiles should be perfectly possible to intercept despite Russian claims to the contrary.

Introduction

Kh-47M2 Kinzhal mounted on the centerline pylon of a Mig-31K

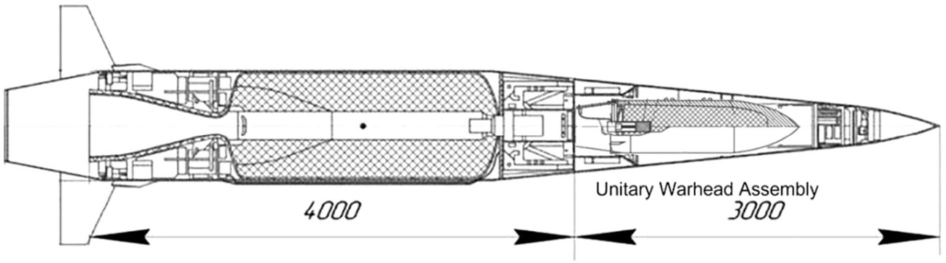
Photo: kremlin.ru

Based on the data that can be found in the public domain, the Kh-47M2 Kinzhal can be configured in a number of different versions with regards to the forward part of the missile (See figures below). In one variant, seen in the second cut-away drawing below, there is a second stage vehicle shown housing the warhead that can separate from the main part of the missile. However, the missile that was purportedly downed by the Ukrainian air defenses on the 4th May 2023 seems to have been of the type where the warhead remains fixed to the main part of the missile as shown in the first drawing below. The basis for this conclusion is that in the pictures and video footage of the missile debris shown by the Ukrainians, this includes the steering fins and what appears to be the ring-shaped part of the Kh-47M2 Kinzhal at the rear of the main body, meaning that the missile used in this attack was in one complete piece when it was intercepted. Consequently, this analysis will be limited to a Kh-47M2 Kinzhal version where there is no second stage vehicle and that the missile's warhead is consequently assumed to remain attached to the missile body for the entire duration of the flight from launch to target. This assumption is also consistent with the pictures released of the debris from the downed missile, which show the heavy mantled penetrator type warhead which can be seen in the cut-away figure immediately below.

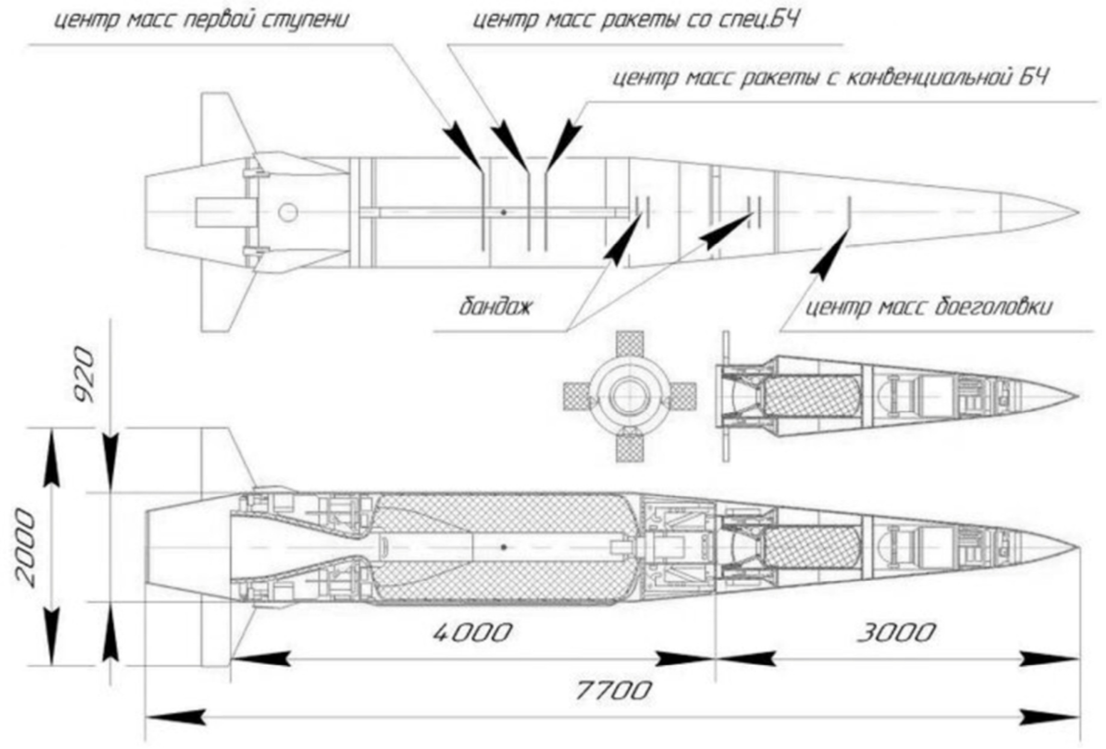
---

[1] Supposedly, there are other aircraft in the Russian Air Force's inventory that can carry the missile, but it is known that the Mig-31K is able to carry a single Kinzhal on its centreline pylon beneath the fuselage.

Sectioned Kh-47M2 Kinzhal missile showing a "Unitary Warhead Assembly"



Sectioned Kh-47M2 Kinzhal missile showing a second stage powered warhead assembly


центр масс первой ступени
центр масс ракеты со спец.БЧ
центр масс ракеты с конвенциальной БЧ
бандаж
центр масс боеголовки
920
2000
4000
3000
7700

Both photos: BTVT Telegram Channel

While sometimes touted in media as a hypersonic missile impossible to detect and intercept[2], the Kh-47M2 Kinzhal is in fact just another large solid fueled surface-to surface (or air-to-ground) missile with a quite limited range to boot. At least when taking into consideration the fact that the "official" 1500-2000 km range[3] figure is for the overwhelming part due not to the missile itself, but to the carrier aircraft's range. In fact, to attain such a range, the carrier aircraft needs to carry the Kinzhal quite close to the target (in the order of 100-400 km) to make up the total purported 1500-2000 km range.

Returning to the question if it's right to class the Kinzhal as hypersonic, a hypersonic missile truly worthy of its name would be one that travels for extended periods of time at hypersonic speeds on its own power and that possesses a reasonable maneuvering capability as well. This means that it needs to be equipped with an engine utilizing the air it flies through as the source of oxygen since in order to achieve any meaningful range at the hypersonic speeds, carrying the oxygen bound in solid fuel would add too much weight and consequently limit its performance severely. This in turn implies a vehicle equipped with a supersonic combustion ram jet or some similar form of advanced propulsion system. Summing up, this describes a missile system that is an order of magnitude more advanced than missiles like the Kinzhal which carry both the fuel and oxidizer inside the missile fuselage and can trace their heritage back to the vintage ballistic missiles like the German V-2[4] rockets used in WW2. Examples of truly hypersonic missiles are the Hypersonic Air-breathing Weapon Concept (HAWC) which in tests has flown at over M=5 for longer than 300 nautical miles, and the scramjet powered Hypersonic Attack Cruise Missile (HACM) currently under development in the USA.

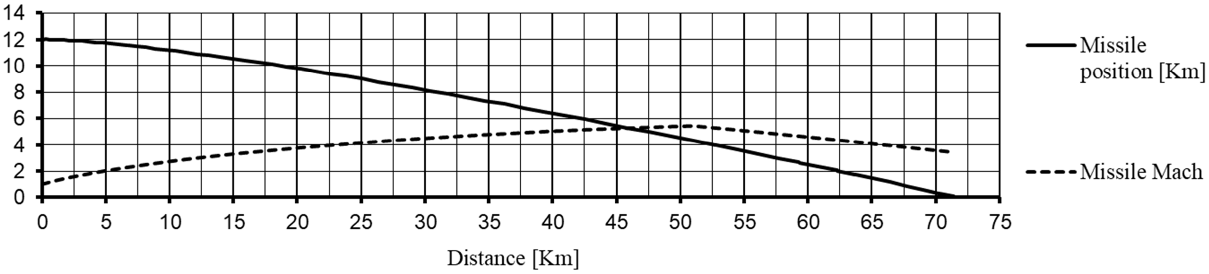
Assumed launch profile and Kinzhal missile kinematics

To illustrate the point of the Kinzhal's limited capability and why it would be wrong to call it hypersonic, below is a figure showing its speed profile when fired in a direct attack mode in a more or less horizontal trajectory. As can be seen, the missile is only above M=5 for about 9 s during the more than a minute flight time and quickly slows down after engine burn-out which makes calling it a hypersonic missile a big stretch.

Kh-47M2 Kinzhal missile flight analysis

Missile assumed launched at M=1 at 12 km altitude with 0.7 g trajectory for about 64 s.

Code used: C++ Missiledata version PA46 assuming start weight 3800 kg, Impulse 94563 Ns, burntime 50 s.



---

[2] According to an article in the Kiev Post posted on the 10th May 2023, Russian Defense Minister Sergei Shoigu claimed in August 2022 that the missile was "impossible to detect or intercept."

[3] This figure is widely quoted and can also be found on the Kh-47M2 Kinzhal page on Wikipedia.

[4] The V-2 rocket was not a solid fuelled powered missile like the Iskander/Kinzhal, but used liquid oxygen and kerosene as fuel. However, this still meant that a substantial part of the missile's take-off weight needed to be allocated to carrying the oxidizer just like for modern solid fuel rocket engines.

Thus having concluded that the Kinzhal cannot really be classed as hypersonic, but given its properties, how can it then be used? While there is no hard distinction between the different modes of attack, two basic modes can be identified: These are the direct attack mode and the ballistic mode:

In the direct attack mode as depicted above, we can see that the Kinzhal only has a range of about 70 km from where it is fired, meaning that the carrier aircraft has to carry the Kinzhal quite close to the intended target. This is then nowhere near the purported 1500-2000 km range and is explained by the fact that in the direct attack mode, the missile flies at lower altitudes for the entire flight time and for a missile going as fast as the Kinzhal, the air at these altitudes will be perceived as very dense by the missile. This in turn leads to very high aerodynamic drag which both limits the top speed attained, and also causes the missile to slow down very quickly once the propellant has burnt out. On the other hand, in the ballistic mode of attack, the Kinzhal would be fired in a steep upward angle and reach altitudes as high as above 100 km if fired at an angle close to 45 degrees. In this case the missile will spend a large part of its flight at altitudes over 12 km where the air is very thin and the aerodynamic drag will therefore be minor, resulting in a very good retention of speed and consequently a close to ballistic trajectory.

However, according to what can be gleaned from media reports, the Kinzhal missiles fired on Kiev have neither been fired in a short range direct or purely ballistical mode, but rather in something in between. While the exact location from where these missiles have been fired has not been disclosed other than that it has been from inside Russian airspace, looking at a map it’s reasonable to assume that this would have been in the order of slightly longer than 300 km from Kiev, since this would have allowed the carrier aircraft to fire the missiles with impunity from within the sanctuary[5] of Russian airspace.

If such a launch distance (over 300 km) is assumed, then this rules out that the Kinzhal was fired horizontally or more or less directly at the target, but rather in an upward angle which in missile parlance is called lofting. And in order for a Kinzhal to reach a bit over 300 km, a lofting angle of around 15 degrees is needed even if a high altitude, high speed launch is assumed. The exact optimal launch angle is dependent on the speed and altitude of the carrier aircraft at launch, but seeing that the Kinzhal is such a big and heavy missile even for a Mig-31K to carry, it’s likely that the carrier aircraft would be limited to flying at around M=1 at an altitude of 12 km when launching the missile. Especially seeing that it has to pull up to an angle of around 15 degrees before performing the attack which would not only slow it down since it’s climbing, but also because of the extra drag due to the g-load needed to change the trajectory from horizontal flight to the loft angle, which would be especially apparent if it’s flying at supersonic speeds. Another option would be for the Mig-31K to change to the 15 degree angle already at lower altitudes and accelerate, but given the added drag and weight of the Kinzhal this would also probably limit the attainable speed significantly. So summing up, a launch speed of M=1 at an angle of around 15 degrees at an altitude of 12 km seems like a reasonable assumption.

Analysis of the possibilities to defeat Kinzhal missile attacks

Leaving the Kinzhal missile kinematics behind for a while and instead turning to the possibilities to intercept the missile before it reached the target, the following analysis indicates that the chances of this should actually be quite good. At least with such a potent missile defense system as the Patriot, and given that the Kinzhal missile would not be traveling at hypersonic speeds when approaching the target in such a scenario. In addition, the Kinzhal would only be able to make very small adjustments of its trajectory on approaching the target assuming these launch conditions. This is in sharp contrast to a truly hypersonic missile powered by a scramjet, which while incapable of really sharp maneuvers, would still be able to change its flight path significantly during the hypersonic approach phase which would keep the defending forces uncertain about the intended target. A scramjet would also have a certain ability to defeat solid fueled air defense missiles (e.g. the Patriot PAC-2[6] or S-400 missile systems) while in transit since it would have the ability to maneuver enough to defeat most of the currently fielded air intercept missiles that rely on aerodynamic surfaces such as the missile's wings or the missile's body to maneuver and maintain a collision course towards the incoming missile. The Patriot PAC-3 missile on the other hand uses an array of impulse imparting small rocket engines that act perpendicular to the flight path and will thus have a higher probability to intercept a fast flying missile like a hypersonic scramjet even if it performs evasive maneuvers. However, whatever the steering principle of the intercepting missile is, it will still need enough kinetic energy to match the incoming missile's speed. This means that the missile defense system, e.g. a Patriot system, needs to be placed in close vicinity to the suspected target in order to make sure that the intercepting missile will have a high enough energy state to make the intercept.

---

[5] At the time these missiles were fired, the Ukrainian rules of engagement forbade (and still do at the time of writing) engaging Russian military assets in Russian air space with NATO supplied hardware.

When it comes to the claimed M=10 top speed of the Kinzhal, this is most likely just as the purported 1500-2000 km range the result of a very liberal definition of the word "capability" since it's simply not physically possible with what we know about the currently fielded single stage Kinzhal. So this figure is either simply erroneous, or a reference to another version of the missile with a warhead section equipped with its own separate solid fuel engine like in the second cut-away drawing above. However, in this figure it is evident that the warhead section located in between the rocket engine and the guidance electronics is of very limited size making this version of the Kinzhal more of a token weapon compared to the more capable warhead type designated the "Unitary Warhead Assembly" in the first cut-away figure. Another possibility could be a specially designed showcase Kinzhal version carrying more internal fuel and none or a very limited warhead. This would allow such a missile to accelerate to the purported M=10 top speed but is just like the 1500-2000 km range figure more of a theoretical propaganda figure.

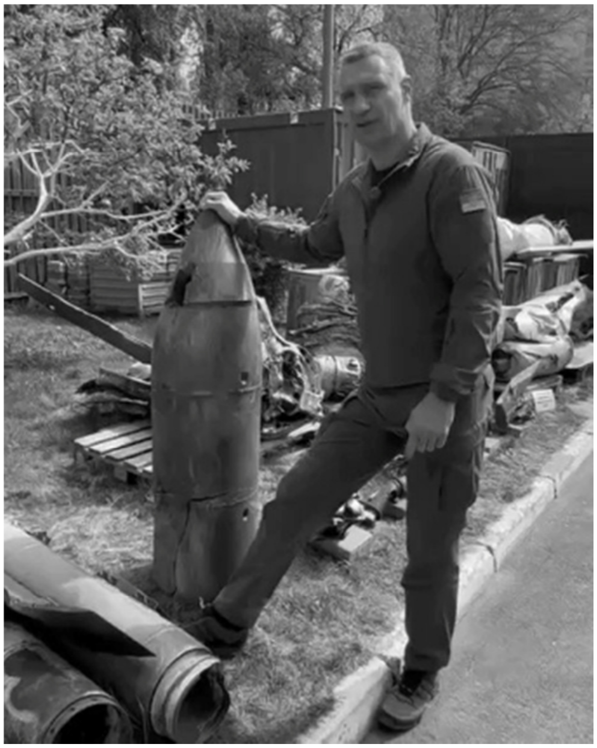
The "Unitary Warhead Assembly" shown in the first Kinzhal cross section figure above is also interesting to compare to some of the pictures that have been circulating in the press accompanied by claims that the Ukrainians have not shot down a Kinzhal but something else. The main argument for this has been that the nose-cone on the Kinzhal bears no resemblance to the pictures released by the Ukrainians claiming to be from a Kinzhal brought down by a Patriot system. Instead, these in many cases pro-Russian sources have claimed that what is shown by the Ukrainians is instead a part of a FAB-500 bomb assembly. However, many of the other pieces shown by the Ukrainian military and claimed to be a part of a downed missile certainly appear to be from a Kinzhal, and the warhead section shown off by the Mayor of Kiev in the picture below certainly does bear a close resemblance to the "Unitary Warhead Assembly" making it quite likely that the Ukrainians did indeed down a Kinzhal utilizing a Patriot battery. Further support to this claim was provided by the US Pentagon Press Secretary Brigadier General Pat Ryder who confirmed that a Kinzhal missile had indeed been brought down by a Patriot system operated by the Ukrainians.

In addition, unverified Ukrainian sources have claimed a very specific velocity of the Kinzhal missile when it was intercepted by the Patriot missile which was in the order of 1250 m/s. This is also consistent with what would be expected in the studied scenario since this would be the expected speed of the Khinzhal (about M=3.8) at a distance of around 6.5 km from the target at an altitude of slightly below 3 km, circa 6 s before the projected target impact time according to the simulation figures below.

---

[6] PAC is the abbreviation for Patriot Anti-tactical-missile Capability.

Kyiv Mayor Vitalii Klitschko showing the Unitary Warhead Assembly from a downed Kh-47 Kinzhal



Picture from bild.de video

Given that it takes the Patriot PAC-2 missile about 12 s to reach full speed (M=5), the Patriot missile should be fired about 12 s before the intercept point. If the intercept point is assumed to be about 6 s before the Kinzhal hits the target, then the Patriot missile consequently needs to be fired about 18 s before the projected target impact time. This in turn means that it needs to be tracked for a few seconds before that in order for the fire control system of the Patriot battery to lock on to the Kinzhal and work out a firing solution. Consequently, in the simulated scenario, the Kinzhal needs to be detected by the Patriot battery about 25 s before impact, i.e. at an altitude of around 13 km and a distance of 33 km from the target. This should be perfectly possible even without forewarning, given the purported max range of 100 km for the Patriot's AN/MPQ-53 radar (about 150 km for the later improved AN/MPQ-65). But it's also highly likely that Ukrainian Patriot batteries receive prior warning through their own radar networks and/or from NATO signals intelligence. In addition, NATO probably keeps a close watch on bases housing Kinzhal capable aircraft like the Mig-31K, and are also sure to identity any aircraft flying a high speed high altitude path consistent with a possible missile attack aimed at Kiev. In addition, it's highly likely that NATO/US assets able to detect missile launches in the Iskander/Kinzhal class (by means of infra-red missile launch detection) are monitoring the situation in Ukraine, and that such information would most likely also be relayed to the Ukrainian air defenses in close to real time. This means that it's highly likely that any Ukrainian Patriot battery with a chance to intercept an incoming missile will be notified, and that the crew will therefore already be on high alert and looking in the right direction, ready to lock on to any incoming Kinzhal missile as soon as this is possible with the Patriot system's own radar system.

Consequently, it's not only theoretically possible for a Patriot battery suitably deployed in Ukraine to intercept a Kinzhal, but also highly likely that the crew would have been suitably forewarned and ready to intercept any incoming missile. The above would also be consistent with reports that parts of a Patriot battery protecting Kiev was damaged in a missile attack, since the debris from a Kinzhal traveling at a speed of around M=3.8 at the time it was intercept would still rain down in the target area with sufficient kinetic energy to do considerable damage. This is also consistent with information gleaned from the media indicating that the intended target in at least one Kinzhal missile attack on Kiev was in fact a Patriot missile battery. This also seems likely not only for the propaganda value of taking out such a highly regarded system, but also since it would have eliminated a serious threat to further Russian attacks on Kiev with 3M54-1 Kalibr cruise and additional Iskander/Kinzhal ballistic missiles.

Further, it should be noted that the analysis in this paper has been centered on the Patriot PAC-2 missile's chances of intercepting a Kinzhal since it is believed that this was the type of missile used by the Ukrainians to down a Kinzhal missile targeting Kiev which was fired from inside Russian territory from a Mig-31K on the 4th of May 2023[7]. However, a Patriot PAC-3 missile will have a much higher kill probability for the studied scenario and others since it does not rely on aerodynamic control surfaces to steer towards the intercept but utilizes a large number of side thrusters to rapidly change the missile's course and can thus achieve a very high hit-to-kill probability.

Minister of Defense of Ukraine Oleksii Reznikov on Twitter 16th May 2023: "Another unbelievable success for the Ukrainian Air Forces! Last night, our sky defenders shot down SIX russian hypersonic Kinzhal missiles and 12 other missiles." If these numbers hold true also in future assessments remains to be seen, and in that case it will undeniably be a major achievement by the Ukrainian air defenses. However, even if new information emerges in the future indicating that this number was optimistic, the simulations have nevertheless shown that intercepting a Kinzhal missile by means of a Patriot missile is well within the bounds of what is theoretically possible looking at both missile's kinematic properties.

Simulation figures showing a Kinzhal missile's flight trajectory

Below are three figures that shows the calculated trajectory and speed history for a Kinzhal missile launched from an aircraft at M=1 at 12 km altitude in a loft angle of 14 degrees.

The following assumptions have been made about the Kh-47M2 Kinzhal in the C++ simulations: Start weight at rocket motor ignition after tail fairing has been jettisoned 3800 kg. Solid fuel rocket motor propellant weight 1913 kg. Specific impulse of rocket fuel 252 s resulting in a total impulse of 4729200 Ns. Burn time of engine assumed to be 50 s giving an average rocket motor thrust of circa 94600 N.

---

[7] Statement published on social media by the head of the Ukrainian Air Force, Lieutenant General Mykola Oleschuk. This was also later confirmed by the US Pentagon Press Secretary Brigadier General Pat Ryder.

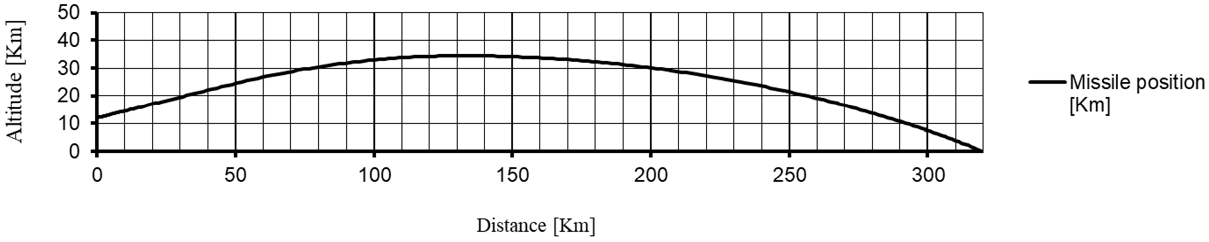
The first figure below shows a representative trace of the Kinzhal's flight path with the same scale on both the x- and y-axis, i.e. a correct depiction of the trajectory, while the figure immediately under it shows the same flight path but with different scales on the x- and y-axis to make a more precise reading of the trajectory values possible.

Note that in the trajectory traced below it has been assumed that the Kinzhal uses a minor amount of aerodynamic lift after the apogee. This allows it to reach the target faster than would be the case with a purely ballistic trajectory which would have given roughly the same range but with more than double the height at the apex and a significantly longer flight time which would give the defenses more time to prepare the intercept.

Kh-47M2 Kinzhal missile flight analysis

Missile assumed launched at M=1 from 12 km altitude with 14 deg loft 0.4 g trajectory after apogee with circa 208 s flight time.

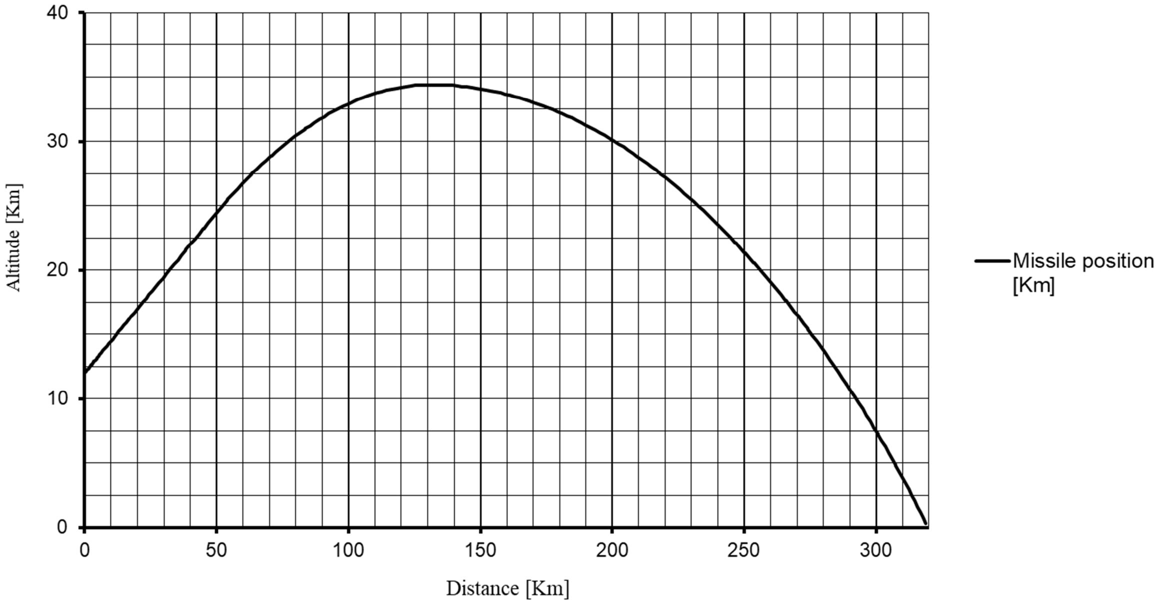
Code used: C++ Missiledata version PA45 assuming start weight 3800 kg, Impulse 94563 Ns, burntime 50 s.



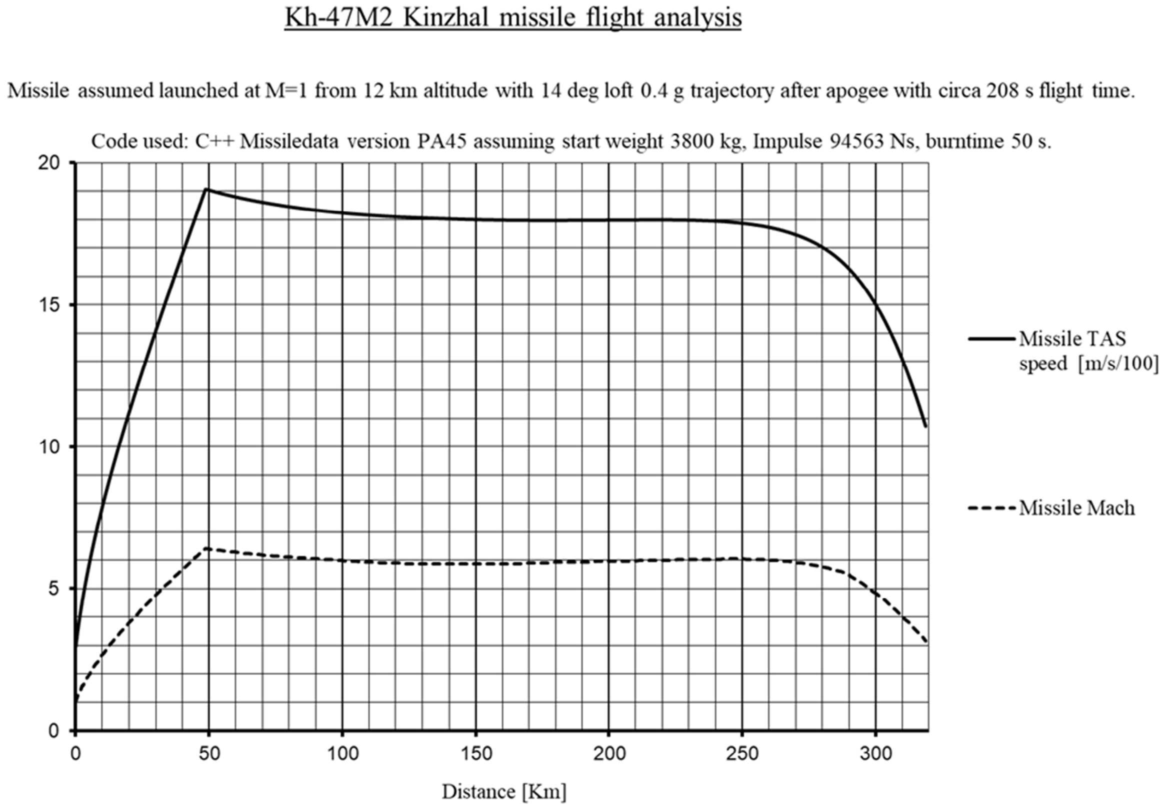
Kh-47M2 Kinzhal missile flight analysis

Missile assumed launched at M=1 from 12 km altitude with 14 deg loft 0.4 g trajectory after apogee with circa 208 s flight time.

Code used: C++ Missiledata version PA45 assuming start weight 3800 kg, Impulse 94563 Ns, burntime 50 s.



The figure below shows the true air speed (TAS) and Mach values along the Kinzhal's trajectory as a function of the distance flown. Note that both the speed and Mach numbers are quite stable for a large part of the flight (almost 70% of the total distance), but that these then drop off rapidly from about 12 km altitude when the missile starts to encounter more dense air in its terminal dive.



Kh-47M2 Kinzhal missile flight analysis

Missile assumed launched at M=1 from 12 km altitude with 14 deg loft 0.4 g trajectory after apogee with circa 208 s flight time.

Code used: C++ Missiledata version PA45 assuming start weight 3800 kg, Impulse 94563 Ns, burntime 50 s.

Conclusions

Summing up, the conclusions that can be drawn from the two simulated scenarios[8] is first of all that the Kh-47M2 Kinzhal will only have speeds that can be described as hypersonic, i.e. over M=5, in the intermediate phases of a lofted trajectory. Secondly, that the speed of the Kinzhal when going terminal and entering the higher air densities at lower altitudes will drop down rapidly so that at the projected impact point with the ground, the Kinzhal's speed would only be in the order of M=3, or 1072 m/s. However, at the supposed interception point at an altitude of around 3 km and at a distance of circa 6 km from the intended target, the Kinzhal's speed will still be in the order of M=3.5 to 4 and around 1100-1300 m/s. Given that the Patriot PAC-2 missile has a burnout velocity of Mach 5 (circa 1500 m/s) about 12 seconds after launch[9], intercepting a Kinzhal at 1200-1300 m/s would be perfectly possible given that the Patriot missile can a speed on par or even a bit higher than the Kinzhal.

However, sometimes the assertion is made that the intercepting missile needs to be traveling much faster than the target in order to hit it, but this is an erroneous assumption since an intercept is still perfectly possible even for scenarios where the missiles speeds are in parity provided that the intercepting missile approaches the target missile's forward hemisphere and that the incoming Kinzhal missile only does small course adjustments in its terminal phase. An analogy to visualize how this is possible could be to mentally picture the forward in a football match running straight towards the goalkeeper to score a goal, while the defender runs in from the side to stop him. If we assume that both players are running at roughly the same speed, it's easy to envision how the defender mentally predicts the forward's path and intercepts him by running a leading course towards a predicted meeting point which is exactly also how a missile's guidance system works.

---

[8] Note that the Kinzhal can reach significantly higher speeds in the terminal phase (over M=5) if shot in a high altitude ballistic scenario from around 500 km away, but in this case the flight time is over 5 minutes.

[9] Technical Debate over Patriot Performance in the Gulf War, Science & Global Security. 1999, Volume 8, J D Sullivan et al.

Paradoxically, the straight head-on scenario may be the most difficult given that the assumed fragment speed of the Patriot's warhead[10] is around 2500[11] m/s and that the warhead needs to be triggered in time since if the missiles pass each other without triggering the warhead's fuse in time, their combined speeds will in many scenarios lead to that the Patriot's warhead fragments will simply not be fast enough to catch the target. However, in most intercept scenarios it's reasonable to assume a certain offset angle between the Patriot's and Kinzhal's trajectory, and in these cases a successful intercept can thus be assumed provided that the Patriot missile passes close enough to the Kinzhal to trigger it's fuse.

---

[10] The missile warhead consisting of around 45 kg 50 g pellets propelled by 40 kg of high-explosive. (From reference in footnote 9).

[11] Video Evidence on the Effectiveness of Patriot during the 1991 Gulf War, Science& Global Security, 1993, Volume4, G N Lewis et al.